Ultrasonic Measurement of Tension in Steel Components of Civil Structures

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Project Overview

- **Goal – Develop an ultrasonic instrument to measure tension in large steel components used in locks and dams**
- **Technical Approach**
  - **Develop necessary ultrasonic theory**
  - **Develop simulator to model wave propagation in components**
  - **Develop a prototype instrument and sensor to make measurements**
  - **Evaluate instrument's capabilities in the laboratory**
  - **Evaluate instrument's capabilities in the field**
- **Progress to Date**
  - **Theory and simulator tasks completed**
  - **Prototype instrument and dual mode sensor designed and built**
  - **Patent disclosure on method and technique filed**
  - **Laboratory evaluation of theory and instrument in progress**

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Project Applications and Benefits

- **Applications**
  - **Dam tainter gate anchor rods**
  - **Lock gate diagonal bracing**
  - **Post-tensioned steel members in bridges and parking garages**
- **Benefits**
  - **Rapidly measures tension in the field**
  - **Works with only limited access to part**
  - **Provides evaluation of fitness for service**
  - **Improves infrastructure reliability**
  - **Decreases maintenance costs**

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Review of Basic Ultrasonic Theory

- Ultrasonic properties are fundamental to the understanding of wave behavior
- Transmission and reflection of ultrasound at interfaces are important for understanding if the sound will stay within the confines of the component
- The angles that waves take upon encountering a boundary are important for understanding where the various modes of sound will go in a field component
- Spreading of ultrasound from a sensor is important for understanding if there will be enough energy received to make the tension measurement

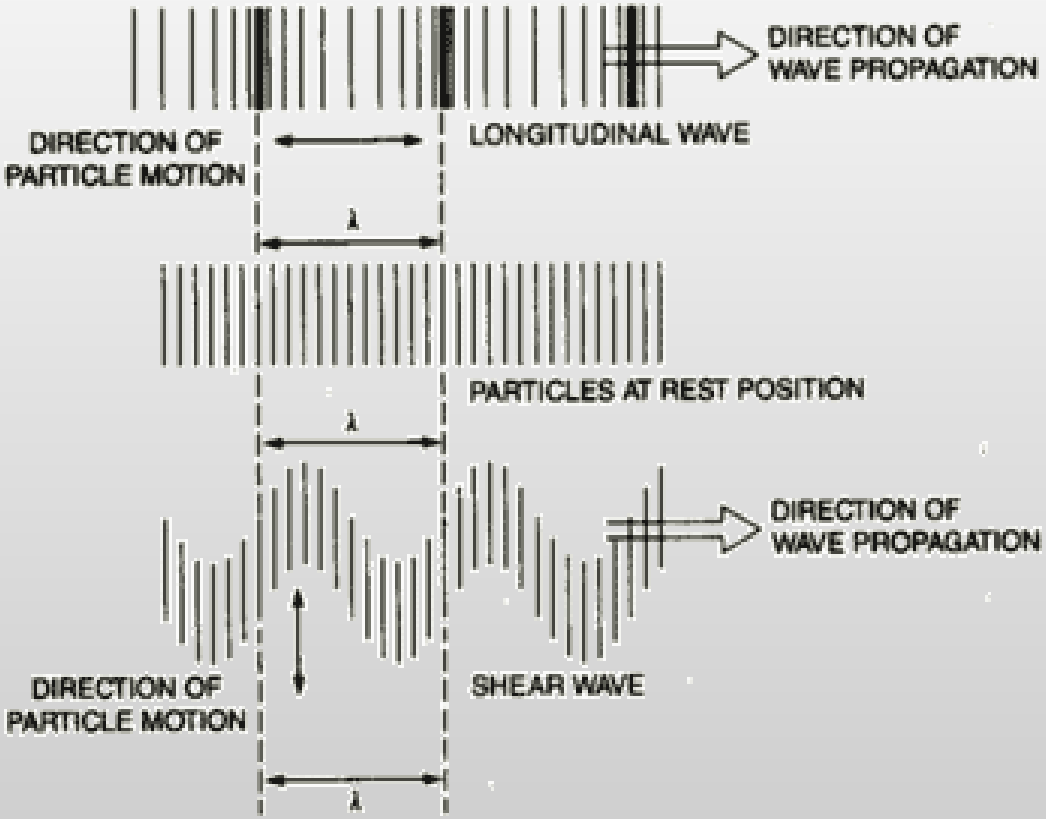
Ultrasonic Properties of Structural Materials

Table I Published Material Properties

	Longitudinal Velocity, V_l (cm/μS)	Shear Velocity, V_s (cm/μS)	Density, ρ (gm/cm^3)	Acoustic Impedance, Z (g/cm^{2}S x 10^6)
Air	0.034	None	1.21 x 10^{-3}	4.15 x 10^{-5}
Aluminum	0.632	0.313	2.73	1.725
Concrete	0.432	--	2.60	1.123
Granite	0.395	--	2.75	1.086
Perspex	0.276	0.143	1.19	0.328
Steel	0.585	0.323	7.80	4.563
Water	0.148	None	1.00	0.148

Ultrasonic wave speeds, density, and acoustic impedance are different for every structural material.

Longitudinal and Shear Waves



In non-porous solid materials, such as metals, there are two propagating ultrasonic waves, longitudinal and shear.

Transmission of Ultrasound at Interfaces Between Materials

$$\alpha_t = 4\,\rho_1 V_1\,\rho_2 V_2 \;/\; (\rho_1 V_1 + \rho_2 V_2)^2 = 4\,Z_1 Z_2 \,/\, (Z_1 + Z_2)$$

$$\alpha_r = \{(\rho_2 V_2 - \rho_1 V_1) \,/\, (\rho_2 V_2 + \rho_1 V_1)\}^2 = \{(Z_2 - Z_1) \,/\, (Z_2 + Z_1)\}^2$$

Table II Transmission and Reflection of Ultrasound at Interfaces

Medium 1	Medium 2	% Transmitted	% Reflected
Steel	Air	0.0036%	99.9964%
Steel	Water	12.17%	87.83%
Steel	Concrete	63.40%	36.60%
Perspex	Steel	25.05%	74.95%
Perspex	Water	85.66%	14.34%
Perspex	Air	0.0505%	99.9495%

The equations, combined with properties from the previous slide, allow the calculation of transmission and reflection coefficients.

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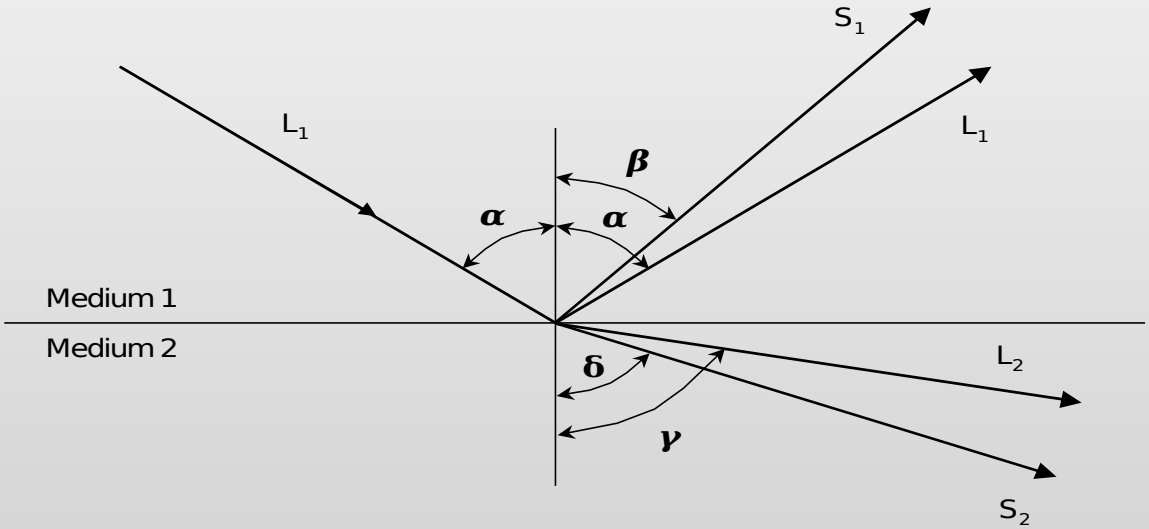
Reflection of Ultrasonic Waves

$$\gamma = \arcsin\left(\sin \alpha \, V_2 / V_1 \right)$$

$$\sin \alpha / V_{l1} = \sin \beta / V_{s1} = \sin \gamma / V_{l2} = \sin \delta / V_{s2}$$

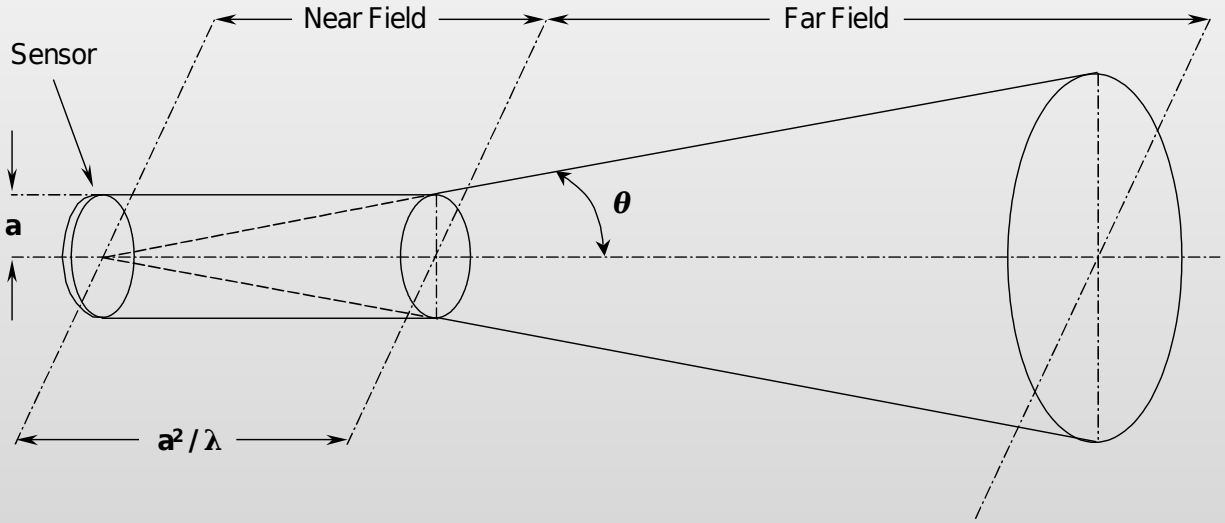


Note: $V_{L1} < V_{L2}$

The equations describe the angle that the wave will take in a specific mode after transmitting or reflecting from an interface.

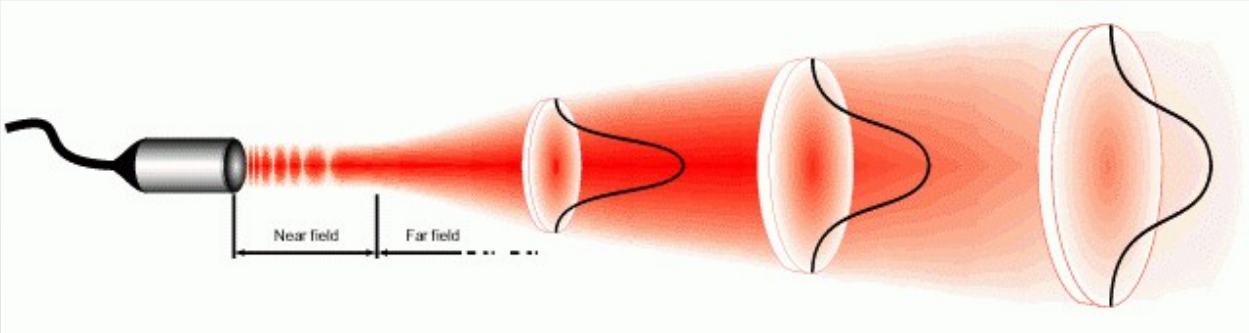
Ultrasonic Beam Spread from a Sensor

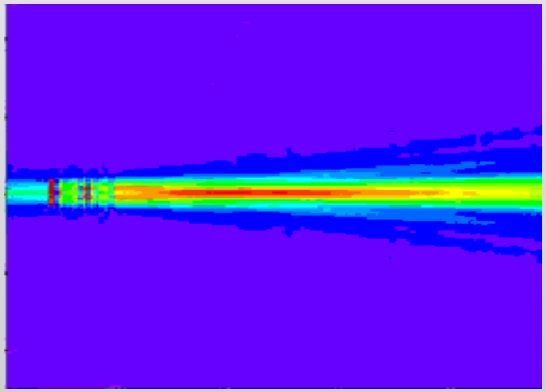
$$\theta = \arcsin(k\,\lambda / 2a)$$

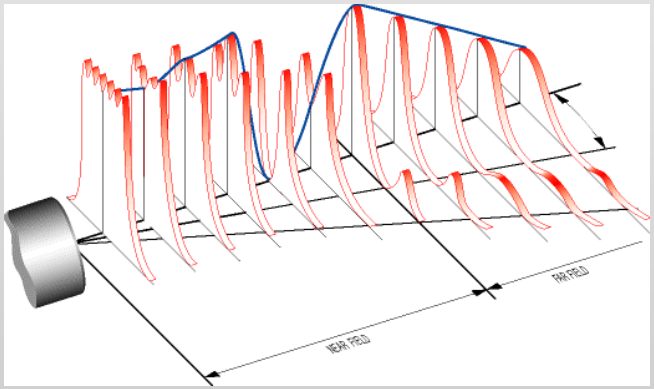


The energy from a sensor spreads in a conical shape as it travels in a component, thus decreasing its energy per unit area.

Ultrasonic Beam Spread from a Sensor (cont'd)







The energy not only spreads, it varies in amplitude depending upon distance from the sensor as well as position across the beam.

Derivation of Ultrasonic Tension Measurement Equation

- Equations describing linear elastic deformation, along with equations describing ultrasonic wave speed, can be manipulated to derive an equation describing how to determine tension inside a material using two ultrasonic measurements
- The elastic deformation quantities include Hooke's Law, the Bulk Modulus, Young's Modulus, the Shear Modulus, and Poisson's Ratio
- To obtain tension ultrasonically, it is only necessary to measure the longitudinal and the shear wave speeds

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Derivation of Ultrasonic Tension Measurement Equation (cont'd)

Hooke's Law

$$\sigma_{ij} = \lambda\, \delta_{ij}\, \varepsilon_{aa} + 2\,\mu\, \varepsilon_{ij}$$

Young's Modulus

$$E = \mu\,(3\,\lambda + 2\,\mu)\,/\,(\lambda + \mu) = \sigma_{zz} / \varepsilon_{zz}$$

Bulk Modulus

$$K = \lambda + 2\,\mu / 3 = \sigma_{xx} / (3\,\varepsilon_{xx}) = \sigma_{yy} / (3\,\varepsilon_{yy}) = \sigma_{zz} / (3\,\varepsilon_{zz})$$

Shear Modulus

$$\sigma_{zx} = 2\,\mu\,\varepsilon_{zx}$$

Poisson's Ratio

$$\nu = \lambda / 2\,(\lambda + \mu)$$

Longitudinal Wave Speed

$$V_l = (c_{11} / \rho)^{1/2}$$

Shear Wave Speed

$$V_s = (c_{44} / \rho)^{1/2}$$

We combined and rearranged the 7 equations above to obtain an equation that relates tension inside a part to two ultrasonic speeds:

$$\sigma = (V_l^2 - 2\,V_s^2) / 2(V_l^2 - V_s^2)$$

Development of a Simulator

- In order to get accurate values for the longitudinal and shear wave speeds, it is necessary to understand how the ultrasound propagates in the part
- A simulator models the part and the sensor, and allows the user to understand which wave component creates particular echoes
- The simulator can also provide some the necessary measurements to obtain tension inside components

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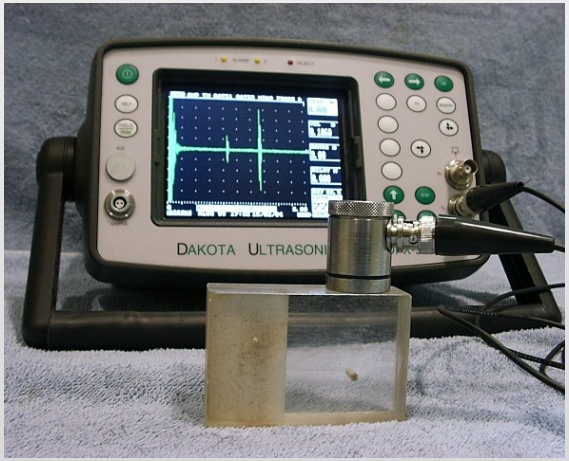
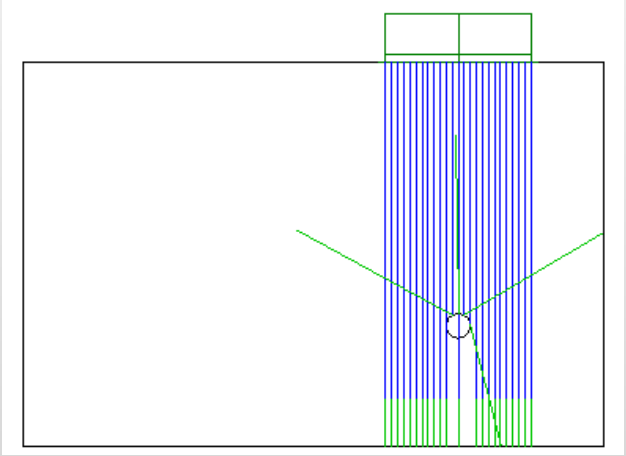
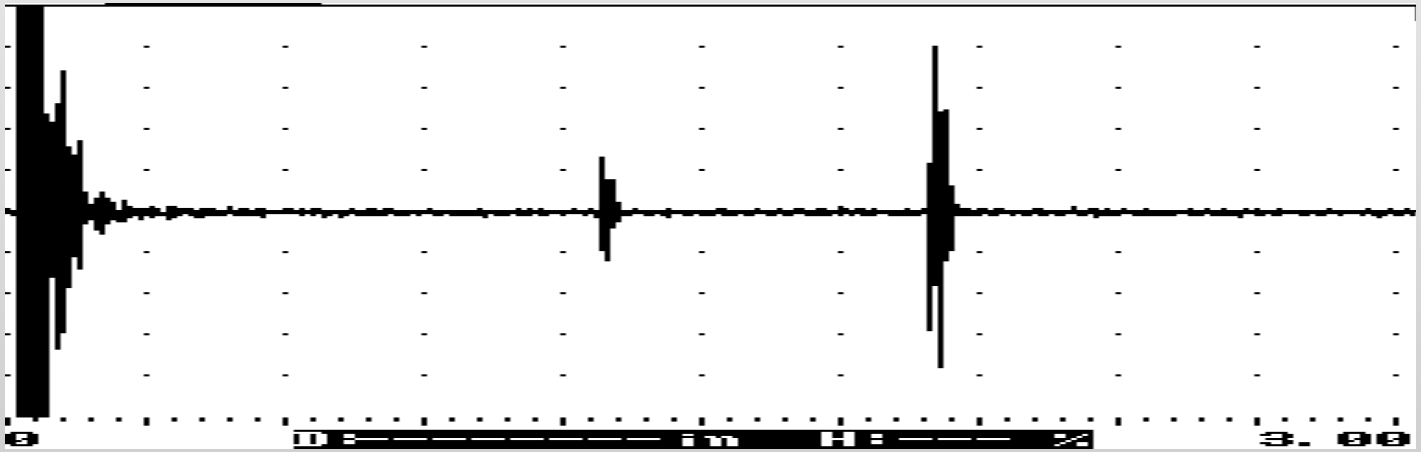
Setup for Simulating Echoes Inside a Plastic Block





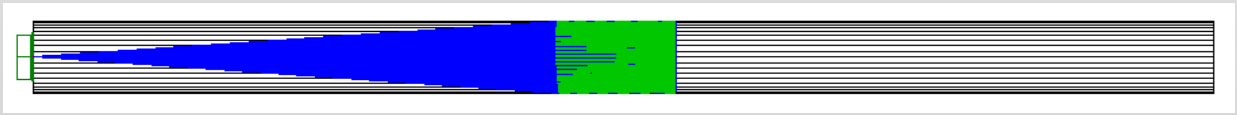
The actual plastic block is on the left (with the echoes showing on the instrument's screen), and the wavefront simulation leading to those echoes is on the right.

Comparison Between Simulation and Reality for a Plastic Block



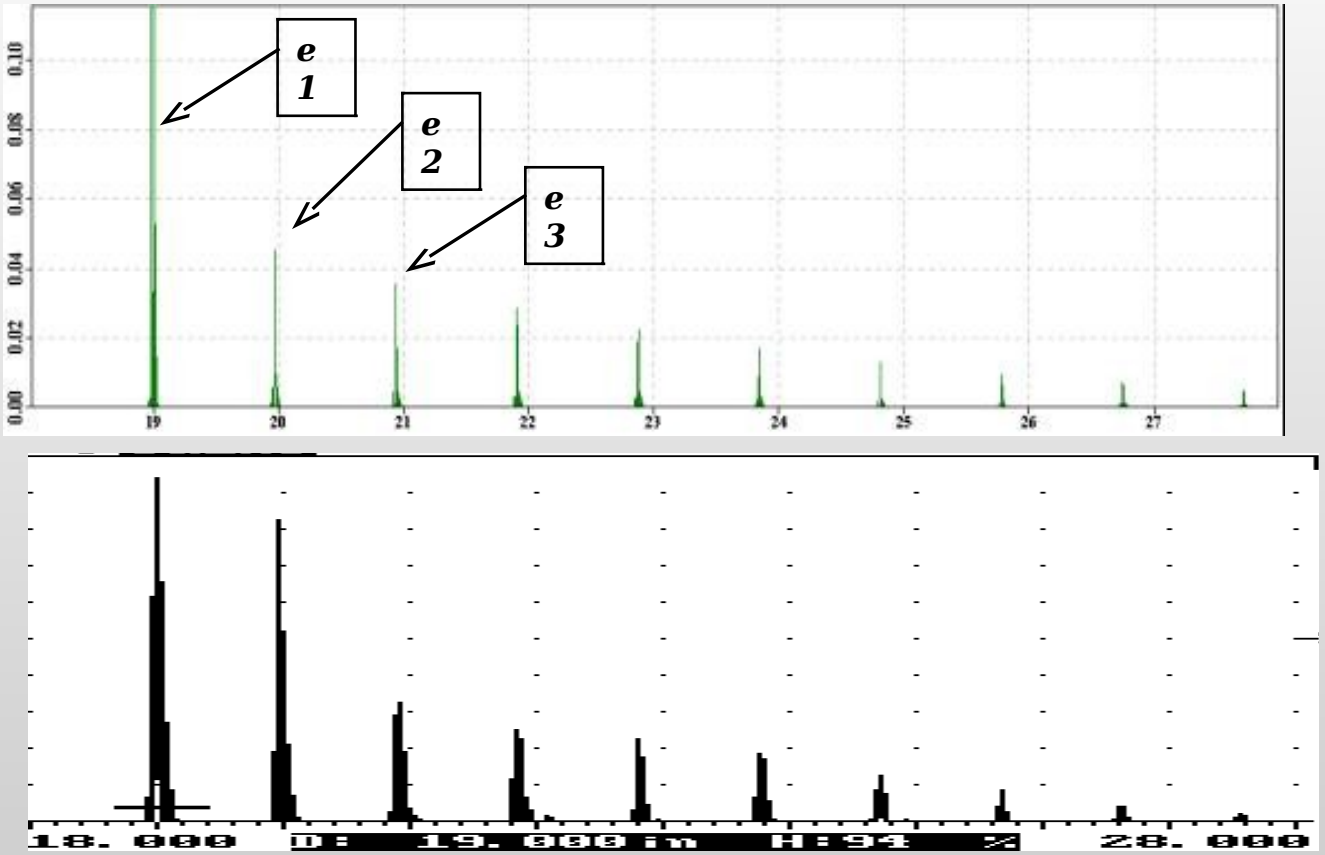
Simulation (top) versus actual instrument results (bottom).

Setup for Simulating Echoes Inside a Steel Rod



The actual steel rod is on the top (with the echoes showing on the instrument's screen), and the wavefront simulation leading to those echoes is on the bottom.

Comparison Between Simulation and Reality for a Steel Rod



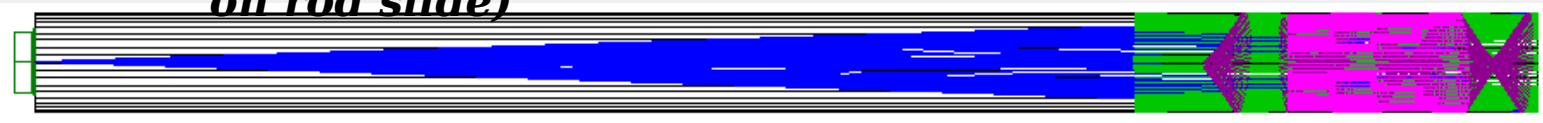
Simulation (top) versus actual instrument results (bottom). The echo times e2 and e3 are used in measuring tension (described later).

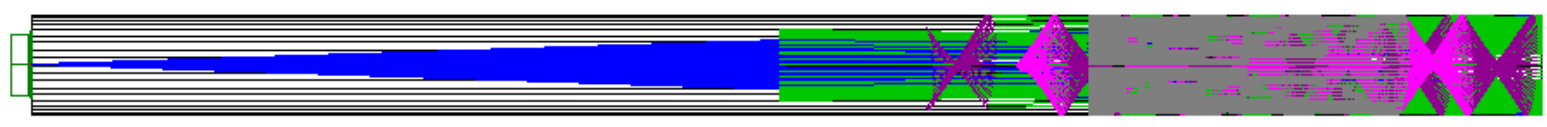
Using Ultrasound to Obtain Tension Measurements

- The key to measuring tension in a component is to obtain both longitudinal and shear wave speeds with a high degree of accuracy. There are two ways to do this:
  - The simulator can be used to obtain the shear wave speed from measurements of two echoes, as well as the longitudinal wave speed, thus enabling the calculation of tension in components
  - A special sensor (which we described in the patent disclosure) can be used to measure longitudinal and shear wave speeds directly (and potentially, more accurately)

Measuring Tension by Using the Simulator

$$t_{e2} = x_2 / V_l + x_3 / V_l + x_4 / V_s + x_5 / V_l$$ *(e2 shown on rod slide)*





$$t_{e3} = x_2 / V_l + x_3 / V_l + x_4 / V_s + x_6 / V_s + x_7 / V_l$$ *(e3 shown on rod slide)*

$$V_s = (x_6 V_l) / (V_l (t_{e3} - t_{e2}) + x_5 + x_7)$$

The simulator can be used to obtain the tension measurement when using only a longitudinal sensor. Two echo times and longitudinal speed are measured; the simulator provides the three path lengths.

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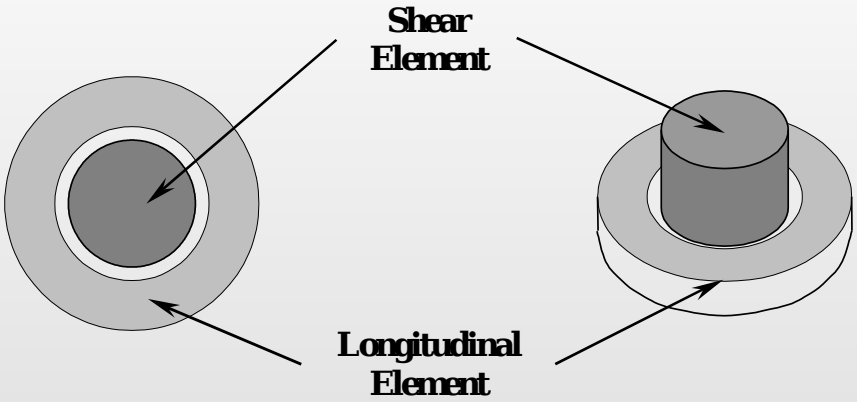
Measuring Tension by Using a Unique Dual Mode Sensor

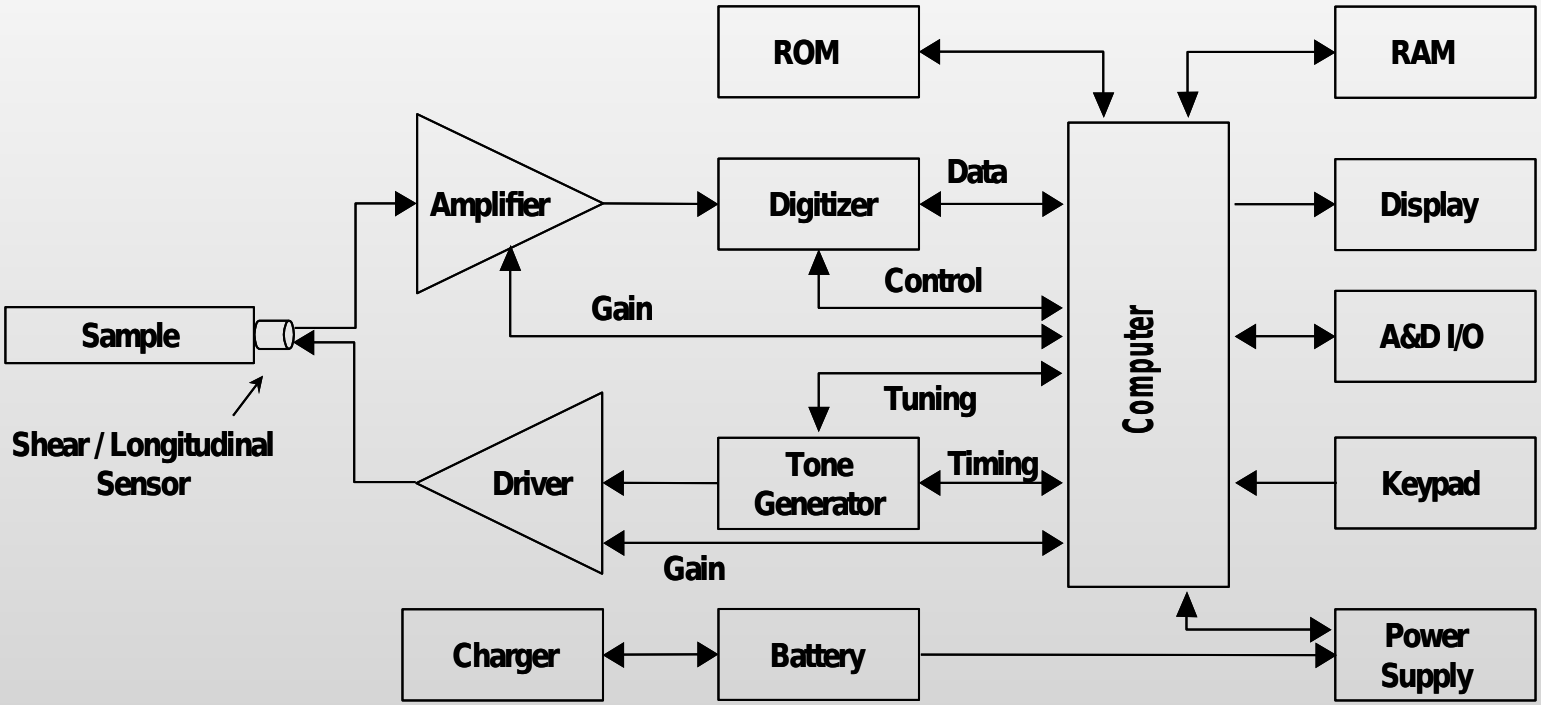


A unique sensor we developed can generate both longitudinal and shear waves from the same housing, permitting the wave speeds of both modes to be measured with a high degree of accuracy.

Moving from Theory to Field

- To be useful, the ultrasonic tension measurement theory must be applicable in field applications:
  - We need a flexible ultrasonic instrument to control the shape of the ultrasonic waveforms, as well as to make the time of flight measurements with sufficiently high accuracy, in order to determine the longitudinal and shear wave velocities
  - We must verify the accuracy of the theory by making tension measurements on actual rods under highly controlled conditions
- The instrument has been designed and built, and laboratory verification of the theory is in progress (next two slides)
- The final task is an actual field test, which is scheduled to take place at the John T. Myers Lock and Dam in Mount Vernon, Indiana, later this summer

Block Diagram of Prototype Instrument



The ultrasonic instrument is designed for maximum flexibility. It features a computer controlled tone generator and digitizer to permit complete control over the ultrasonic waveforms.

Laboratory Verification of the Theory

- We have procured a load frame to place sample rods in tension.
- Unique grips are being made that will minimize stress field anomalies inside the rod under test
- The grips also permit free access to the rod ends for sensor placement
- Direct comparison can be made between ultrasonically measured tension and load applied to the rod

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Field Verification of Technique

The field test of the ultrasonic tension measurement technique is scheduled to take place at the John T. Myers Lock and Dam in Mount Vernon, Indiana, later this summer.

Conclusions and Future Work

- **Conclusions**
  - **Developed a means of measuring tension ultrasonically**
  - **Developed an ultrasonic simulator to predict wave propagation and help make tension field measurements easier**
  - **Developed a unique sensor to make the tension measurement more accurate in the field**
  - **Submitted a patent disclosure on the new method**
  - **Developed a prototype instrument**
  - **Laboratory evaluation of instrument and verification of the theory is presently being conducted**
- **Future Work Plans**
  - **Field evaluation of instrument scheduled for later this summer**

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